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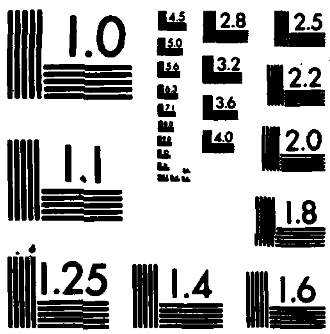

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TUNABLE OPTICAL SOURCES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Solid state lasers, slab lasers, Nd:Glass, Nd:YAG, Nd:GGG Nonlinear Optics, Optical parametric oscillation, $AgGaS_2$ Crystal growth, $AgGaSe_2$, Urea $MgO:LiNbO_3$.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A detailed theoretical description of thermal stress and optical propagation characteristics for high average power solid state lasers has been developed. Experimental research has progressed through three generations of glass slab laser devices and has been extended to crystalline slab lasers. The growth technology of new nonlinear materials has been investigated. Optical parametric oscillation has been achieved in silver thiogallate.

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TUNABLE OPTICAL SOURCES

Robert L. Byer

I. STATEMENT OF PROBLEM STUDIED

The objective of this study has been to advance the understanding and state-of-the-art of tunable coherent sources. The main areas of investigation have been the development of neodymium-doped-glass slab lasers, and the generation of tunable radiation by nonlinear optical conversion. This research is motivated by a number of applications including X-ray generation in laser produced plasmas for high resolution imaging and lithography, and the generation of tunable coherent radiation for remote sensing of atmospheric constituants and conditions.

Slab geometry solid state lasers offer significant performance improvements over conventional rod geometry lasers. Thermally induced distortions in optical propagation are compensated in the zig-zag path through the slab, and laser average power capability is limited by material failure rather than optical distortion. The slab concept was first discussed in 1969 by Martin and Chernoch at General Electric. Effects related to the finite size of actual laser slabs made it difficult to realize the theoretical performance of an infinite slab. Also engineering design problems, particularly those of heat dissipation, were more difficult with the slab geometry than with rod geometry. Our investigation of slab lasers has addressed these topics through theoretical

analysis and numerical modeling of high average power slab lasers combined with experimental measurements and verification of our predictions. We have extended the slab laser concept to increasingly larger glass laser systems and to new crystalline materials.

A program in efficient, high average power nonlinear optical generation of tunable coherent radiation requires devolpment of pump sources, improved nonlinear materials, and nonlinear techniques. Slab laser devices provide one source for diffraction limited high average power pump radiation required for practical nonlinear conversion. We have also continued research in the growth technology of existing and new nonlinear optical materials. The materials which we have investigated include $AgGaS_2$, $AgGaSe_2$, urea, and MgO doped $LiNbO_3$. We are continuing to investigate other materials, but this is a particularly interesting group of nonlinear crystals which together provide coverage from 214 nm in the ultraviolet to 17 micrometers in the infrared. Each of these materials has unique features which in some way extends the range of performance of available nonlinear materials. As the new materials become available they are evaluated experimentally with various nonlinear conversion techniques.

II. SUMMARY OF MOST IMPORTANT RESULTS

A. Slab Laser Development

The theoretical analysis and numerical modeling of slab laser performance is one of the most important results of this program. A paper describing this

analysis, "The Slab Geometry Laser, I-Theory," is scheduled to be published in the March 1984 issue of the IEEE Journal of Quantum Electronics. The model allows us to calculate the thermal stress and resulting optical wavefront distortions and birefringence in a laser slab pumped at high average power. The model includes the effects of nonuniform pumping and edge cooling. The dependence of laser performance on slab geometry and material characteristics is calculated. Accurate predictions of optical distortion and stress fracture limitation are obtained from the model.

The theoretical analyis and numerical model has been an important tool in extending slab-glass lasers technology to larger sytems and extending the slab laser investigation to include crystalline laser materials. Our initial experimental studies and verification were performed with a test bed neodymium:glass slab laser designed and built as part of this program. The test bed slab operated as a free running laser at 10 J per pulse and 2 Hz with the stress fracture limit occuring at 25-W average output power. We are currently completing the design and assembly of an oscillator-amplifier slab system which will operate in the Q-switched mode at 10 Hz repetition rate with 10-J per pulse output energy. Our model predicts that the amplifier of this system could be operated as a free running laser with 300-W average output power.

The technique of static gas conduction cooling of the slabs is a significant engineering development resulting from this investigation. Direct contact of coolant liquids on the reflecting surfaces of the slab result in surface contamination and lower optical damage thresholds, and make the problems of sealing the coolant flow more difficult. Other engineering problems such as

improved efficiency in the coupling of pump radiation to the slab and optimum neodymium concentration of the laser glass have been studied. It has been shown that it is feasible to construct a moving slab glass laser that could have output powers of greater than 1 KW.

We have also performed slab laser experiments with crystalline materials. A Nd:YAG slab was substituted for a Nd:YAG rod in a commercial cw laser sytem. The performance of the slab was as good as the rod for multi-mode unpolarized output. However, the slab was superior for single transverse mode output and far superior for polarized output. CW laser oscillation was attained for the first time in the laser material Nd:GGG (neodymium doped gadolinium gallium garnet). This demonstration showed the potential of the slab laser technique for obtaining high average power in laser materials that have high dn/dT. This is an important application for new laser materials such as Cr-Nd:GScGG and other co-activated garnets which provide better efficiency than Nd:YAG but do so at the expense of less satisfactory thermal properties such as higher dn/dT.

B. Tunable Nonlinear Optical Conversion

We have continued to investigate nonlinear optical conversion and the growth technology and application of nonlinear optical materials. The materials $AgGaS_2$, $AgGaSe_2$, and urea have been grown in good optical quality. Preliminary evaluation has been performed on 5% MgO doped $LiNbO_3$, and optical parametric oscillation has been attained in a chalcopyrite crystal, $AgGaS_2$.

Nonlinear optics in the infrared has been limited by available nonlinear materials. Several of the chalcopyrite crystals have attractive nonlinear and linear optical properties, but had not been grown in sizes or quality required. We chose to initiate studies with $AgGaS_2$ because its visible transparency proved advantageous in crystal growth studies. Recent investigations at the Stanford Center for Materials Research have led to significant improvements in crystal quality and size. Currently both $AgGaS_2$ and $AgGaSe_2$ crystals are grown by a seeded vertical Bridgman method in a sealed fused silica ampoule. Seeding to initiate growth along the c-axis eliminates cracking and twinning. Boules of 2.8-cm diameter by 10-cm length have been grown with good yield. Following growth the crystals are heated treated in the presence of excess Ag_2S or Ag_2Se to eliminate absorption and scattering centers.

Optical parametric oscillation has been achieved with $AgGaS_2$ pumped with 1.064-micrometer radiation from a Q-switched Nd:YAG laser. Tuning of the OPO from 1.4 to 4.0 micrometer was demonstrated. The material has the potential for continuous tuning out to the 12-micrometer transparency limit. OPO performance was limited by the 2-cm crystal length and low surface damage threshold of the material. Both increased damage threshold and the use of longer crystals would improve OPO performance.

The first crystals of $AgGaSe_2$ of good optical quality and greater than 1-cm length have only recently been grown. Nonlinear optical experiments have not yet been performed with this material. The transparency range of $AgGaSe_2$ extends from 0.9 to 17 micrometers, and its nonlinear coefficient is four times

that of $AgGaS_2$. $AgGaSe_2$ should be an excellent material for second harmonic generation of CO_2 laser radiation. Parametric oscillators pumped at 1.32 or 2 micrometers has the potential of tuning to 17 micrometers.

Urea is another nonlinear optical crystal which has recently been grown at The Center for Materials Research and is awaiting evaluation. Urea is interesting for its transparency and phasematching properties in the ultraviolet and its high optical damage threshold in that spectral region.

We are also preparing to evaluate 5% MgO doped $LiNbO_3$. This nonlinear optical material also has been obtained only in the last few weeks. Original samples of 5%-MgO:$LiNbO_3$ were supplied by Professor Han Kai of Chengdu Institute of Technology on a visit to Stanford in 1982. After a preliminary evaluation, samples of the material were given to Bob Rice at McDonell-Douglas who sponsored a crystal growth study at Crystal Technology, Inc.
We have only obtained material grown by Crystal Technology in the last few weeks.

C. Future Directions

Development of our 10-J, 10-Hz, Q-switched glass slab oscillator amplifier is continuing. Initial experiments using this laser for soft X-ray generation are planned for mid-1984. Research is continuing in both glass and crystalline slab lasers. Both materials have charteristics useful for high average power laser applications. Glass laser material is available in excellent optical

quality in large size and it is relatively inexpensive. Crystalline laser materials offer higher mechanical strength and better thermal properties, but optical quality is not as good as glass, size is limited and expense is often high.

Recent improvements in nonlinear optical materials and high average power laser pump sources should result in significant advances in the generation of tunable coherent radiation by nonlinear conversion. We will immediately proceed with the evaluation of the three new nonlinear materials, $AgGaSe_2$, 5%-$MgO:LiNbO_3$, and urea, while continuing investigation of other nonlinear materials. Our program will also include further development of pump sources, techniques of nonlinear optical conversion, and theoretical analysis.

III. SCIENTIFIC PERSONNEL SUPPORTED BY THIS CONTRACT

Principal Investigator	Professor Robert L. Byer Applied Physics Dept.
Research Professor	Robert S. Feigelson, Center for Materials Research
Senior Research Associates	Roger K. Route Center for Materials Research
	Robert C. Eckardt Ginzton Laboratory of Physics
Students	John M. Eggleston (Ph.D. 1982) Thomas Kane Kelin Kuhn Murray Reed John Trail Keith Bennett (Ph.D. 1984) William Kozlovsky

IV. LIST OF ALL PUBLICATIONS AND PRESENTATIONS

A. Publications

1. R.L. Byer, Y.K. Park, R.S. Feigelson, and W.L. Kway, "Efficient Second Harmonic Generation of Nd:YAG Laser Radiation Using Warm Phasematching $LiNbO_3$," Appl. Phys. Lett., vol. 39, p. 17, 1 July 1981.

2. Y.K. Park and R.L. Byer, "Electronic Linewidth Narrowing Method for Single Axial Mode Operation of Q-switched Nd:YAG Lasers," Opt. Commun., vol. 37, p. 411, 15 June 1981.

3. J.M. Eggleston, G. Giuliani and R.L. Byer, "Radial Intensity Filters Using Radial Birefringent Elements," J. Opt. Soc. Am., vol. 71, 1981.

4. J.M. Eggleston, T.J. Kane, J. Unternahrer and R.L. Byer, "Slab Geometry Nd:Glass Laser Performance Studies," Opt. Lett., vol. 7, p. 405, 1982.

5. Y.L. Sun and R.L. Byer, "Sub-Megahertz Frequency Stabilized Nd:YAG Oscillator," Optics Letters, vol. 7, p. 408, 1982.

6. R.L. Byer, T.J.Kane, J. Eggleston and Sun Y. Long, "Solid State Laser Sources for Remote Sensing, published in Optical and Laser Remote Sensing, Eds. D.K. Killinger and A. Mooradian, p. 245, Springer, New York, 1982.

7. J.M. Eggleston, T. Kane, K. Kuhn and R.L. Byer, "Progress In Slab Geometry Solid State Lasers," S.P.I.E. vol. 335, Advanced Laser Technology and Applications, 1983.

8. T. Kane, R.C. Eckardt and R.L. Byer, "Reduced Thermal Focusing and Birefringence in Zig-Zag Geometry Crystalline Lasers," IEEE J. Quantum Electron., vol QE-19, p. 1351, 1983.

9. Y.K. Park, G. Giuliani and R.L. Byer, "Single Axial Mode Operation of a Q-Switched Nd:YAG Oscillator by Injection Seeding," IEEE J. Quantum Electron., vol. QE-20, pp. 117-125, Feb. 1984.

10. J. Eggleston, T. Kane, K. Kuhn, J. Unternahrer and R.L. Byer, "The Slab Glass Laser - Theory," to be published in the IEEE J. Quantum Electron., 1984.

11. T. Kane and R.L. Byer, "A Proposed 1 Kilowatt Average Power Nd:Glass Moving Slab Laser," submitted to the IEEE J. Quantum Electron., 1984.

12. K. Kuhn, T. Kane, M. Reed, J. Unternahrer and R.L. Byer, "Static Gas Conduction Cooled Slab Geometry Nd:Glass Laser," in preparation.

B. Invited Presentations

1. Robert L. Byer, "Progress In Nd:YAG Pumped Tunable Sources," Army Rrsearch Office Topical Conference on Tunable Lasers, Keystone, Colorado, April 2, 1981.

2. Robert L. Byer, "Progress in Nd:Glass Slab Lasers," Los Alamos Optical Conference, Santa Fe, NM, April 10, 1981.

3. Robert L. Byer, "Status of Remote Sensing Technology," Conference on Lasers and Electro-Opticss, paper WI 1, Washington, D.C., June 10, 1981.

4. Robert L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cw Molecular Beam CARS Spectroscopy," International Laser Spectroscopy Conference, Jasper, Canada, July 1981.

5. Robert L. Byer, "Progress in Tunable Lasers," I.B.M. Research Laboratory, San Jose, CA, Nov. 10. 1981.

6. R.L. Byer "Progress in Slab Configuration Lasers," Naval Research Laboratory, Washington, D.C., Feb. 2, 1982.

7. R.L. Byer, "Slab Geometry Lasers," S.P.I.E. Meeting, Washington, D.C., May 6, 1982.

8. R.L. Byer, "Laser Sources for Remote Sensing," National Bureau of Standards-DoD Conference on Chemical Detection Methods, July 20, Washington, D.C., 1982.

9. R.L. Byer, "High Power Solid State Slab Geometry Lasers," T.R.W., Burbank, CA, Oct. 1, 1982.

10. R.L. Byer, "Progress in CARS Spectroscopy", and "Recent Advances in Solid State Lasers," Tsinghua University and Shanghai Laser Institute, China, Nov. 1982 (Member of IEEE Delegation to China).

11. R.L. Byer, "Material Aspects of Solid State Lasers," Seminar at Center for Materials Research, Stanford University, 1983.

12. R.L. Byer, "Advances in Lasers," Industrial Affiliates Meeting, Chemistry and Physics Departments, Stanford University, Feb. 1983.

13. R.L. Byer, "Progress in High Peak and Average Power Slab Geometry Solid State Lasers," Norwegian Optical Society Meeting, Oslo, Norway, March 1983.

14. R.L. Byer, "Slab Geometry Solid State Lasers," Physics and Chemistry Affiliates Program, Stanford University, March 28, 1983.

15. R.L. Byer, "Conduction Cooled Slab Geometry Lasers," Lawrence Livermore National Laboratory, Livermore, CA, June 15, 1983.

16. T. Kane and R.L. Byer, "Coherent Doppler Wind Measurements using Neodymium Lasers," 2nd Topical Meeting on Coherent Laser Radar, Aspen Colorado, Aug. 1, 1983.

17. K. Kuhn and R.L. Byer, "Progress in Nonlinear Crystals and Slab Geometry Lasers," Nonlinear optics Gordon Conference, Aug. 1, 1983.

18. R.L. Byer, "Progress in Slab Geometry Solid-State Lasers," invited paper TuO4, Optical Society of America - Annual Meeting, New Orleans 17-20 Oct. 1983.

C. Contributed Presentations

1. E. Gustafson, J. McDaniel and R.L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," paper WO1, Conference on Lasers and Electro-Optics, Washington, D.C., June 1981.

2. M.D. Duncan and R.L. Byer, "Characterization of a Pulsed Supersonic Molecular Beam Using CARS," paper ThF1, Conference on Lasers and Electro-Optics, Washington, D.C., June 1981.

3. R.L. Byer, T. Kane , J. Eggleston and Sun Yun Long, "Solid State Laser Sources for Remote Sensing," Workshop on Optical and Laser Remote Sensing, Monterey, California, Feb. 1982.

4. J.M. Eggleston, T. Kane and R.L. Byer, "Slab Geometry Solid State Lasers," Conference on Lasers and Electro-Optics, Phoenix, Arizona, April 1982.

5. T. Kane, J. Eggleston and R.L. Byer, "Polarized cw Nd:YAG Laser Using a Slab Geometry." Conference on Lasers and Electro-Optics, Phoenix, Arizona, April 1982.

6. Y.L. Sun and R.L. Byer, "A Sub-Megahertz Frequency Stabilized Nd:YAG Oscillator," Conference on Lasers and Electro- Optics, Phoenix, Arizona, April 1982.

7. J.M. Eggleston, T. Kane, K. Kuhn and R.L. Byer, "Progress in Slab Geometry Solid State Lasers," S.P.I.E. Meeting, Washington, D.C., May 1982.

8. J. Eggleston, T. Kane , R.L. Byer and J. Unternahrer, "Slab Geometry Solid State Lasers," International Quantum Electronics Conference, Munich, June/July 1982.

9. T. Kane and R.L. Byer, "A Proposed Kilowatt Average Power Nd:Glass Laser," paper WE2, 1982 Annual Meeting of the Optical Society of America, Tucson, Arizona Oct. 18-22, 1982.

10. K. Kuhn, T. Kane, and R.L. Byer, "Conductive Cooling of Slab Glass Lasers," paper WE3, 1982 Annual Meeting of the Optical Society of America, Tucson, Arizona Oct. 18-22, 1982.

11. Y.X. Fan and R.L. Byer, "An Infrared $AgGaS_2$ Optical Parametric Oscillator," post deadline paper, Conference on Lasers and Electro-Optics, Baltimore, MD, May 17-20, 1983.

12. J.R. Unternahrer, H.P. von Arb and R.L. Byer, "Tunable Nd:Glass Slab Laser," paper TuO6, Optical Society of America - Annual Meeting, New Orleans, Louisiana, Oct. 17-20, 1983.

13. R.L. Byer and Y.X. Fan, "Progress in Optical Parametric Oscillators," paper 461-17, S.P.I.E. Technical Symposium, Los Angeles, CA, Jan. 22-27, 1984.

14. D.C. Brown, K.J. Kuhn and R.L. Byer, "Amplified Spontaneous Emission in Slab Lasers," submitted for presentation at the XII International Conference on Quantum Electronics, Anaheim, CA, June 18-21, 1984.

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